

# Voltage-controlled intracavity electromagnetically induced transparency with asymmetry quantum dots molecule

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## Abstract

We theoretically investigate the phenomenon of voltage-controlled intracavity electromagnetically induced transparency with asymmetric double quantum dot system. The impact of voltage on frequency pulling and cavity linewidth narrowing are discussed. The linewidth and position of the cavity transmission can be engineered by the bias voltage. The scheme may be useful in integrated electro-optical device in quantum information process.

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Electromagnetically induced transparency (EIT) [1, 2], as a useful technology, has received much attention for its potential applications in a wide domain, such as enhancement of nonlinear optical processes [3], quantum coherent control [4], and quantum information and memory [5–7]. An EIT medium placed in a cavity can substantially affect the properties of the resonator system and significantly narrow the cavity linewidth, which is known as intracavity-EIT termed by Lukin and co-workers [8]. Later, many EIT-based works have been carried out in optical resonator with atomic system, such as optical bistability and multistability [9], photon-photon interaction [10], slow light [11, 12], cavity-linewidth narrowing by EIT with hot [13] and cold [14] atomic-Rb system respectively, and so on.

Quantum dot (QD) is three-dimensional confined semiconductor nanostructure in which electrons and holes exhibit discrete energy levels [15]. This atomic-like property allows us to treat dynamical evolution of a QD system with similar methods in atomic physics. Unlike atoms, they can be customized as expected. Moreover, a QDs system has many advantages than an atomic system, such as high nonlinear optical coefficients, large electric-dipole moments and ease of integration, which make it as a promising candidate for quantum information processing. Great progresses in the fabrication and physics of single quantum dots focus people's attention on coupled quantum dots [16]. For example, an asymmetric quantum dot molecule (QDM) consists of two QDs with different band structures which is coupled by tunneling. A near resonance incident light can excite an electron from the valence to the conduction band in a dot, and the electron can tunnel to the other dot. The tunneling effect is sensitive to external bias voltage, then the interdot oscillations can be controlled by the applied voltage. Many works have been carried out about the asymmetric QDM system, such as coherent control of electron tunneling [17], optical signature of asymmetric QDM [18], voltage-controlled slow light [19] and pulse storage and retrieval [20], etc. The flexible QDM combined with the excellent optical and electrical technology exhibits an attractive prospect in integrated electro-optical devices in quantum information process.

Optical cavity is a useful tool for investigation of light-matter interaction and provides us many principle demonstrations which inspires us to extend these results to other fields. In recent years, much attention has been paid to the investigation of a quantum dot-cavity system. These include cavity-coupled resonance fluorescence [21], strong-coupling interaction [22–24], dark-polarization soliton [25], quantum bistability [26], cavity-assistance generation of entangled photon [27–29], and so on. Some of us have also studied transmission spectrum of a double quantum-dot-nanocavity system in photonic crystals [30].

Intrigued by these studies, in this paper we combine asymmetric QDM sample with optical resonator and theoretically describe the phenomenon of an intracavity-induced transparency controlled by voltage. When a QDM sample is placed inside an optical resonator, the cavity field can couple its interband transition. In the presence of the bias voltage, the interdot tunneling is enhanced, which affects its optical property. Then voltage-controlled tunneling replace pump laser coupling the interdot transition, and the two transitions consist of an EIT configuration [16]. Therefore, we can control the intracavity EIT by voltage, which results in frequency pulling and cavity-linewidth narrowing. The asymmetric QDM can be simplified as the model in Fig. 1(a). The ground state  $|0\rangle$  is the system without excitation and the exciton state  $|1\rangle$  has a pair electron and hole bound in the first dot. The indirect exciton state  $|2\rangle$  contains one hole in the first dot and an electron in the second dot, and it is coupled with  $|1\rangle$  by the electron tunneling. A probe field couples  $|0\rangle \leftrightarrow |1\rangle$  transition with Rabi frequency  $g = -\mu_{10}E_p/2\hbar$ , where the electric dipole moment  $\mu_{10}$  denotes the coupling to the radiation field of the excitonic transition, and  $E_p$  is the amplitude of the probe field.

According to the standard procedure [31], we get the dynamical equations of the QDM sample in the interaction picture and in the rotating wave approximation:

$$\begin{aligned}
\dot{\rho}_{00} &= \gamma_{10}\rho_{11} + \gamma_{20}\rho_{22} + ig(\rho_{01} - \rho_{10}), \\
\dot{\rho}_{11} &= -\gamma_{10}\rho_{11} + iT_e(\rho_{12} - \rho_{21}) + ig(\rho_{10} - \rho_{01}), \\
\dot{\rho}_{22} &= -\gamma_{20}\rho_{22} + iT_e(\rho_{21} - \rho_{12}), \\
\dot{\rho}_{10} &= -(i\Delta + \Gamma_{10})\rho_{10} - ig(\rho_{00} - \rho_{11}) - iT_e\rho_{10}, \\
\dot{\rho}_{20} &= -[i(\Delta - \omega_{12}) + \Gamma_{20}]\rho_{20} + ig\rho_{21} - iT_e\rho_{10}, \\
\dot{\rho}_{12} &= -(i\omega_{12} + \Gamma_{12})\rho_{12} - iT_e(\rho_{22} - \rho_{11}) - ig\rho_{02},
\end{aligned} \tag{1}$$

together with  $\rho_{kj}^* = \rho_{jk}$  and the closure relation  $\sum_j \rho_{jj} = 1$  ( $j, k \in \{0, 1, 2\}$ ). Here  $\gamma_{jk}$  is lifetime broadening linewidth, and  $\Gamma_{jk}$  is dephasing broadening linewidth which is usually the dominant mechanism and can be controlled by adjusting barrier thickness in QDM. The detuning  $\Delta = \omega_{01} - \omega_p$  and the energy difference  $\omega_{12} = \omega_{02} - \omega_{01}$ .  $T_e$  is the electron-tunneling matrix element. In the following, all parameters are scaled by  $\Gamma_{10}$ , which is about in the order of meV for (In,Ga)As/GaAs [16, 18].

Consider the QDM system being initially in the ground state  $|0\rangle$ ,  $\rho_{00}^{(0)} = 1$  and  $\rho_{11}^{(0)} = \rho_{22}^{(0)} = \rho_{21}^{(0)} = 0$ , and weak field approximation. By solving the Eqs. (1), the linear susceptibility is given

by[19]:

$$\begin{aligned}\chi(\omega) &= \chi' + i\chi'', \\ \chi' &= \left\{ -\Delta\Gamma_{20} - (\Delta - \omega_{12})[T_e^2 - \Delta(\Delta - \omega_{12})] \right\} / \mathcal{D}, \\ \chi'' &= \left\{ -\Gamma_{10}(\Delta - \omega_{12})^2 - \Gamma_{20}(\Gamma_{10}\Gamma_{20} + T_e^2) \right\} / \mathcal{D}, \\ \mathcal{D} &= (\Gamma_{10}\Gamma_{20} - \Delta^2 + \Delta\omega_{12} + T_e^2)^2 + [\Delta\Gamma_{20} + (\Delta - \omega_{12})\Gamma_{10}]^2,\end{aligned}\tag{2}$$

where  $T_e$  and  $\omega_{12}$  can be simply tuned with bias voltage [17]. It is easy to see that, when the probe field detuning is zero ( $\Delta = 0$ ) and the bias voltage turns off ( $T_e = 0$ ), the real part of the linear susceptibility  $\chi'$  is zero but its image part still exists ( $\chi'' \neq 0$ ). It indicates there is a big absorption around the resonance frequency  $\omega_{01}$ , so the probe field is absorbed. When the tunneling  $T_e$  increases, EIT arises and a transparency window appears at the position where  $\chi''$  is zero [19], which requires  $\Delta \approx \omega_{12}$  according to the material parameters in Ref. [33]. It means that the position of the transparency window varies with  $\omega_{12}$ . This provides the feasibility of engineering the QDM response at different frequencies simply by modulating the bias voltage.

Here, we consider an optical ring cavity of length  $L$  with an asymmetric QDM sample of length  $l$ . The real part  $\chi'$  of the susceptibility of the medium brings dispersion and additional phase shift, and the imaginary part  $\chi''$  introduces absorption leading to the attenuation of the field's amplification. When an empty cavity resonance frequency  $\omega_c$  is near to the EIT frequency  $\omega_{01}$  of the QDM, the resonance frequency  $\omega_r$  of the cavity+QDM system is governed by [8]

$$\omega_r = \frac{1}{1 + \xi} \omega_c + \frac{\xi}{1 + \xi} \omega_{01}, \tag{3}$$

where  $\xi = \omega_{01}(l/2L)(\partial\chi'/\partial\omega_p)$  describes dispersion changes as a function of probe frequency. By considering  $\Gamma_{20} \ll \Gamma_{10}$  [33], the dispersion in the transparency window ( $\Delta = \omega_{12}$ ) is approximately given by

$$\frac{\partial\chi'}{\partial\omega_p} \approx \frac{-T_e^4 + T_e^2(\Gamma_{20} - 2\Gamma_{10}\Gamma_{20} + 2\Gamma_{20}\omega_{12}^2)}{(T_e^3 + 2T_e\Gamma_{10}\Gamma_{20})^2}. \tag{4}$$

To a given system, the dispersion strongly depends on the tunneling. Without the QDM sample, the resonance frequency is the empty-cavity frequency. When the QDM sample is placed in the resonator and the tunneling turns on,  $\omega_r$  is pulled strongly to  $\omega_{01}$ . By changing the bias voltage, the tunneling could be enhanced or suppressed, which leads to different degree of frequency pulling. This pulling effect can be represented quantitatively by the stabilization coefficient  $\xi$ . To get a better frequency-stabilization effect, we just need to tune the bias voltage to a proper value.

It is instructive to examine the modified cavity linewidth [8]

$$\Delta\omega = \frac{\Delta\omega_0(1 - r\kappa)}{\sqrt{k}(1 - r)} \frac{1}{1 + \xi}, \quad (5)$$

where  $\Delta\omega_0$  is an empty-cavity linewidth and  $\kappa = \exp(-kl\chi'')$  is the medium absorption per round trip. Without tunneling, the QDM sample becomes a two-level system. Large dispersion  $\partial\chi'/\partial\omega$  goes with big absorption, and the probe field is absorbed. However, if the tunneling turns on, EIT occurs with larger dispersion and weak (or zero) absorption which much narrows the cavity linewidth. At the transparency window, Eq. (5) reduces to  $\Delta\omega = \Delta\omega_0/(1 + \xi)$ . Since the coefficient  $\xi$  depends on the tunneling, then we can control the cavity linewidth by the bias voltage. Under the different strength of the tunneling, we examine the modified cavity transmission. The rate of the cavity linewidth,  $\Delta\omega$  and  $\Delta\omega'$ , under the different tunneling reads

$$\frac{\Delta\omega}{\Delta\omega'} = \frac{1 + \omega'_r(l/2L)[(\partial\chi')'/\partial\omega_p]}{1 + \omega_r(l/2L)(\partial\chi'/\partial\omega_p)} \approx \frac{(\partial\chi')'/\partial\omega_p}{\partial\chi'/\partial\omega_p}. \quad (6)$$

It is easy to see that the cavity linewidth is reversely proportional to the dispersion. Different tunneling controlled by bias voltage leads to different dispersion in transparency window, then different linewidths of cavity transmissions can be achieved.

Figure 2 shows the cavity transmission under different conditions and all parameters are scaled by  $\Gamma_{10}$  for simplicity. Empty cavity transmission is plotted in Fig. 2(a). When the asymmetric QDM sample is embedded in the cavity but the bias voltage turns off, the QDM sample can be considered as two-level system, then the probe field is absorbed [see Fig. 2(b)]. Whereas, if the bias voltage turns on, the tunneling increases and the QDM sample becomes an EIT system. So we get a narrow transmission peak [see Fig. 2(c)]. Here, the bias voltage replaces the pump field coupling the interdot transition and EIT occurs in the asymmetric QDM sample. Larger dispersion appears in the transparency window and it much narrow the cavity transmission. Since the cavity linewidth is inverse to the dispersion around the transparency window, when the dispersion decreases by tuning the bias voltage, the cavity transmission becomes broad [see Fig. 2(e)]. Then we achieve the voltage-controlled intracavity EIT. Moreover, the narrow transmission peak shifts with the variation of  $\omega_{12}$  [see Fig. 2(d)], which can also be simply controlled by the bias voltage. That is to say that we can engineer the cavity response by the QMD sample at a broad frequency range.

Also, we present a 3D demonstration of the variation of the dispersion with  $T_e$  and  $\Gamma_{10}$  in Fig. 3. It shows that the dispersion changes with  $T_e$  in different QDM vary widely. When the decoherence

( $\Gamma_{10}$ ) is small, fine-tuning voltage in the magnitude range  $0 \sim 0.5$  leads to the dramatic change of the dispersion. While, to a QDM sample with large decoherence, this change tends to gentle. Then, as required, we can prepare an appropriate QDM sample or control its decoherence by tuning its temperature.

Experimentally the self-assembled lateral QDM can be grown by molecule beam epitaxy combining with *in situ* atomic layer precise etching [32]. In the following calculation, the material parameters consult Ref. [19, 33]. The surface density is  $4 \times 10^{10} \text{cm}^{-2}$  with the optical confinement factor  $\Gamma = 6 \times 10^{-3}$ . The laser wavelength is  $1.36 \mu\text{m}$  and  $|\mu_{10}|/e = 21 \text{\AA}$ . The linewidth value for  $\hbar\Gamma_{10}$  are  $6.6 \mu\text{eV}$  and  $\Gamma_{20} = 10^{-4}\Gamma_{10}$ . At  $T_e = 0.01$ , the calculated dispersion from Eq. (5) is  $-4.5 \times 10^3$ , which means we could get the cavity-linewidth narrowing factor of  $10^3$ . This may be useful in weak-electricity-controlled high-resolution spectroscopy and laser frequency stabilization. What's more, when the bias voltage turns on / off, the probe field transmits / is absorbed. This may be used to measure small electric field and also as an electro-optic switch.

In conclusion, we theoretically discussed the effect of voltage-controlled EIT to a resonator with the asymmetric QDM sample. Frequency pulling and cavity-linewidth narrowing are discussed. The voltage-controlled tunneling replaces pump laser coupling interdot transition, which composes an EIT process with the probe transition. An appropriate tunneling leads to larger dispersion which much narrows cavity linewidth. Moreover, by tuning the external voltage, we can engineer cavity response at different frequency. This scheme combines excellence optical and electrical technology, and the voltage-controlled EIT may have potential application in integrated electro-optical device in quantum information process.

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### List of Figure Captions

Fig. 1. Schematic band structure and level configuration of an asymmetric quantum dot molecule (QDM) system for electromagnetically induced transparency process. An input laser field excites an electron from the valence band to the conduction band in a dot that can tunnel to the other dot.

Fig. 2. Cavity transmission as a function of probe-field detuning  $\Delta$ . (a) Empty-cavity transmission. Cavity+QDM transmission for (b)  $T_e = 0$ ,  $\omega_{12} = 0$ ; (c)  $T_e=0.5$ ,  $\omega_{12} = 0$ ; (d)  $T_e=0.5$ ,  $\omega_{12} = 0.2$ ; (e)  $T_e=1$ ,  $\omega_{12} = 0$ .

Fig. 3. Dispersion at EIT window as a function of tunneling  $Te$  in different QDM samples whose linewidth vary from  $6\mu\text{ev}$  to  $50\mu\text{ev}$  assuming  $\Gamma_{20} = 10^{-4}\Gamma_{10}$ . For a better view, the dispersion above 7 are not been plotted.

Figure 1

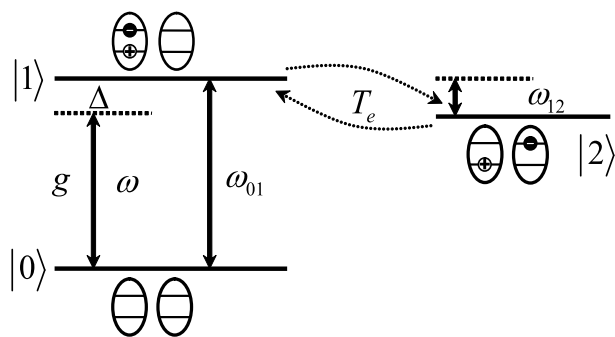


Figure 2

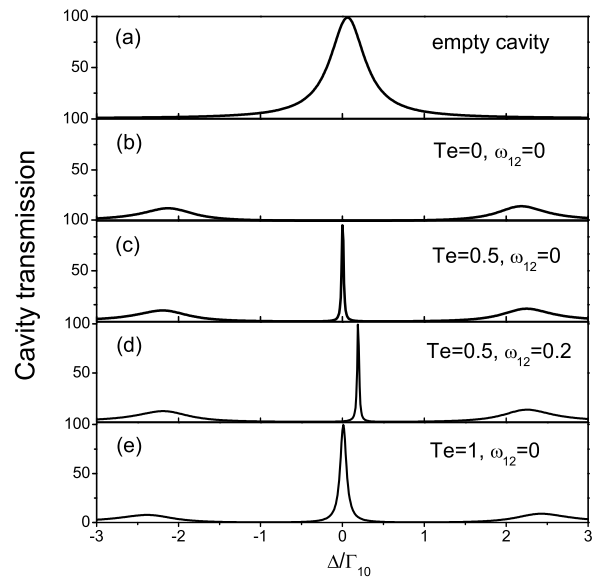


Figure 3

